Neutrino Superbeams and the Magic Baseline

A. Asratyan*, G.V. Davidenko, A.G. Dolgolenko, V.S. Kaftanov,
M.A. Kubantsev†, and V. Verebryusov

Institute of Theoretical and Experimental Physics,

B. Cheremushkinskaya St. 25, Moscow 117259, Russia

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Abstract

We examine the sensitivity to $\nu_\mu \to \nu_e$ of a conceptual experiment with a neutrino superbeam incident on a Megaton-scale water Cherenkov detector over a "magic" baseline ∼7300 km. With realistic beam intensity and exposure, the experiment may unambiguously probe $\sin^2 2\theta_{13}$ and the sign of Δm^2_{31} down to $\sin^2 2\theta_{13} \sim 10^{-3}$.

Detecting the subdominant oscillation $\nu_\mu \to \nu_e$ on the "atmospheric" scale of L/E has emerged as a priority for long-baseline accelerator experiments. This is because the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ probabilities are sensitive to yet-unknown parameters of neutrino mixing: the mixing angle θ_{13}, the sign of the "atmospheric" mass-squared difference Δm^2_{31}, and the CP-violating phase δ_{CP} [1]. However, extracting the values of these parameters from measured probabilities will encounter the problem of degenerate solutions [2]. In particular, the asymmetry between $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ may arise from either the intrinsic CP violation and the matter effect

*Corresponding author. Tel.: + 7-095-237-0079; fax: + 7-095-127-0837; *E-mail address:* asratyan@vitep1.itep.ru.

†Now at Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA.

that is correlated with the sign of Δm^2_{31} [3]. The degeneracies can be resolved by comparing the data taken with a shorter and longer baselines [4]. Selecting the latter as the "magic" baseline $L_{\rm magic} \simeq 7300$ km will render this strategy particularly effective: for $L = L_{\rm magic}$, all Δm^2_{21}-induced effects like CP violation are predicted to vanish up to second order of the small parameter $\Delta m^2_{21}/\Delta m^2_{31}$ [2, 5]. Therefore, selecting $L = L_{\rm magic}$ may allow to uniquely determine $\sin^2 2\theta_{13}$ and the sign of Δm^2_{31}, but not δ_{CP} which should be probed with a shorter baseline.

In this paper, we discuss a conceptual experiment that involves a neutrino "superbeam" incident on a water Cherenkov detector over a magic baseline of $L =$ 7340 km[1]. A water Cherenkov target is selected on the merit of good separation and spectrometry of electromagnetic showers [6], and is assumed to be a megaton-scale detector like UNO or Hyper-Kamiokande [7]. In tuning the energy of the neutrino beam, one must take into account that the E_ν-dependence of oscillation probability for $L = 7340$ km is strongly affected by Earth matter: for $\Delta m^2_{31} > 0$, the matter effect [3] shifts the first maximum of $P(\nu_\mu \to \nu_e)$ down to $E_\nu/\Delta m^2_{31} \simeq 2.5 \times 10^3$ GeV/eV^2 from the vacuum value of 5.9×10^3 GeV/eV^2. Assuming $\Delta m^2_{31} = 0.003$ eV^2, the oscillation maximum is at $E_\nu \simeq 7.5$ GeV which conveniently matches the peak of ν_μ flux in the "Medium-Energy" (or PH2me) beam of Fermilab's Main Injector, as designed for the NuMI–MINOS program [8]. Therefore, this is selected as the model beam in our simulation. We assume 1.6×10^{21} protons on neutrino target per year, as expected upon the planned upgrade of Main Injector's intensity [9]. In the absence of oscillations, the beam will produce some 58 ν_μCC (21 $\bar{\nu}_\mu$CC) events per 1 kton$\times$yr in the far detector with the ν ($\bar{\nu}$) setting of the focusing system.

At neutrino energies below 1 GeV, as in the proposed JHF–Kamioka experiment [10], ν_e appearance can be efficiently detected in a water Cherenkov apparatus by selecting 1-ring e-like events of the reaction $\nu_e N \to e^- X$ that is dominated by quasielastics. (Here and in what follows, X denotes a system of hadrons other than the π^0, in which the momenta of all charged particles are below the Cherenkov threshold in water.) At substantially higher energies considered in this paper, using the 1e signature of $\nu_\mu \to \nu_e$ is complicated by more background from the flavor-blind NC reaction $\nu N \to \nu \pi^0 X$: its cross section increases with E_ν, and so does

[1]This is chosen to match the distance from Fermilab to Gran Sasso or from CERN to Homestake.

the fraction of π^0 mesons whose $\gamma\gamma$ decays produce a single e-like ring in the water Cherenkov detector[2]. In [12], we have demonstrated that ν_e appearance can be analyzed with less NC background by detecting the reactions $\nu_e N \to e^-\pi^+ X$ and $\nu_e N \to e^-\pi^0 X$ that involve emission of a charged or neutral pion[3]. We proceed to briefly describe the selections of these CC reactions, as formulated in [12].

The reaction $\nu_e N \to e^-\pi^+ X$ is selected by requiring two rings in the detector, of which one is e-like and the other is non-showering and has a large emission angle of $\theta_\pi > 50^0$. This is referred to as the "$e\pi$ signature". The selection $\theta_\pi > 50^0$ is aimed at suppressing the NC reaction $\nu p \to \nu\pi^0 p$ in which the momentum of the final proton is above the Cherenkov threshold[4]. The residual NC background is largely due to the reaction $\nu N \to \nu\pi^0\pi^\pm X$ with two pions in the final state. The ν_μCC background arises from the reaction $\nu_\mu N \to \mu^-\pi^0 X$ in which the muon is emitted at a broad angle. The ν_τCC background arises from the dominant oscillation $\nu_\mu \to \nu_\tau$ followed by $\nu_\tau N \to \tau^-\pi^+ X$ and $\tau^- \to e^-\nu\bar{\nu}$.

The reaction $\nu_e N \to e^-\pi^0 X$ is selected by requiring either three e-like rings of which two fit to $\pi^0 \to \gamma\gamma$, or two e-like rings that would not fit to a π^0. This is referred to as the "multi-e signature". The NC background arises from the reaction $\nu N \to \nu\pi^0\pi^0 N$ in which at least one of the two π^0 mesons has not been reconstructed. Note that in the latter reaction the two π^0 mesons are emitted with comparable energies, whereas in $\nu_e N \to e^-\pi^0 X$ the e^- tends to be the leading particle. This suggests a selection based on the absolute value of asymmetry $A = (E_1 - E_2)/(E_1 + E_2)$, where E_1 and E_2 are the energies of the two showers for the two-ring signature, and of the reconstructed π^0 and the "odd" shower—for the three-ring signature. In this paper, we use the selection $|A| > 0.6$. The ν_τCC background is largely due to electronic decays of τ leptons produced in association with a π^0. The ν_μCC background originates from CC events with a muon below the Cherenkov threshold and two π^0 mesons in the final state, and is negligibly small.

In the simulation, the matter effect is accounted for in the approximation of uniform matter density along the neutrino path ($\langle\rho\rangle = 4.3$ g/cm^3 for $L = 7340$ km),

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[2]This happens when the opening angle is too small for the two showers to be resolved [11].

[3]Here and below, corresponding antineutrino reactions are implicitly included.

[4]This reaction may also be rejected by identifying relativistic protons by ring shape, as proposed in [13].

which adequately reproduces the results of exact calculations for the actual density profile of the Earth [3]. Relevant neutrino-mixing parameters are assigned the values consistent with the atmospheric and reactor data [14, 15]: $\Delta m^2_{31} = \pm 0.003$ eV^2, $\sin^2 2\theta_{23} = 1$, and $\sin^2 2\theta_{13} = 0.01$ (the latter value is ten times below the upper limit imposed in [15]). The simulation relies on the neutrino-event generator NEUGEN based on the Soudan-2 Monte Carlo [16], that takes full account of exclusive channels like quasielastics and excitation of baryon resonances.

The $E_{\rm vis}$ distributions of 1e-like, $e\pi$-like, and multi-e-like events are illustrated in Fig. 1, assuming $\Delta m^2_{31} > 0$ and incident neutrinos. Here, $E_{\rm vis}$ stands for the net energy of all e-like rings. Total background to the $\nu_\mu \to \nu_e$ signal is seen to be the greatest for 1e-like events, and therefore we drop these from further analysis. Combined $E_{\rm vis}$ distributions of $e\pi$-like and multi-e-like events are shown in Fig. 2 for either beam setting and either sign of Δm^2_{31}. With equal ν and $\bar\nu$ exposures of 1 Mton$\times$yr, the oscillation signal reaches some 250 events for $\Delta m^2_{31} > 0$ and incident neutrinos, and some 140 events for $\Delta m^2_{31} < 0$ and incident antineutrinos.

The experimental strategy we adopt is to share the overall exposure between the ν and $\bar\nu$ running so as to equalize the expected backgrounds under the $\nu_\mu \to \nu_e$ and $\bar\nu_\mu \to \bar\nu_e$ signals, and then analyze the difference between the $E_{\rm vis}$ distributions for the ν and $\bar\nu$ beams. The motivation is that many systematic uncertainties on the background should cancel out in the difference[5]. The ν and $\bar\nu$ backgrounds are approximately equalized by running 1.7–1.8 times longer in the $\bar\nu$ mode than in the ν mode (see Fig. 2). The difference between the $E_{\rm vis}$ distributions for the ν and $\bar\nu$ beams, assuming ν and $\bar\nu$ exposures of 1.0 and 1.8 Mton$\times$yr, is illustrated in Fig. 3. Depending on the sign of Δm^2_{31}, this distribution shows either a bump or a dip at oscillation maximum with respect to the background that corresponds to $\sin^2 2\theta_{13} = 0$.

In order to estimate the significance of the oscillation signal in Fig. 3, we vary the $E_{\rm vis}$ interval so as to maximize the "figure of merit" $F = (S_\nu - S_{\bar\nu})/\sqrt{B_\nu + B_{\bar\nu}}$. Here, S_ν and $S_{\bar\nu}$ are the numbers of $\nu_\mu \to \nu_e$ and $\bar\nu_\mu \to \bar\nu_e$ events falling within the $E_{\rm vis}$ interval, and B_ν and $B_{\bar\nu}$ are corresponding numbers of background events. We

[5]This is particularly important here, as the large dip angle of the neutrino beam ($\sim 35^0$) will rule out the construction of a "near" water Cherenkov detector.

obtain $F = +19.6$ for $\Delta m^2_{31} > 0$, and $F = -20.8$ for $\Delta m^2_{31} < 0$. Recalling that these figures refer to $\sin^2 2\theta_{13} = 0.01$, we estimate that at 90% CL the sensitivity to either $\sin^2 2\theta_{13}$ and the sign of Δm^2_{31} will be maintained down to $\sin^2 2\theta_{13} \simeq 8 \times 10^{-4}$. Still lower values of $\sin^2 2\theta_{13}$ may perhaps be probed with a neutrino factory in combination with a magnetized iron–scintillator detector [17, 5]. Note however that the experimental scheme proposed in this paper is based on proven technology and involves a multi-purpose facility [7] rather than a dedicated detector.

To summarize, we have examined the physics potential of an experiment with a neutrino superbeam that irradiates a Megaton-scale water Cherenkov detector over the "magic" baseline ∼7300 km. With realistic beam intensity and exposure, the experiment may probe $\sin^2 2\theta_{13}$ and the sign of Δm^2_{31} down to $\sin^2 2\theta_{13}$ values below 10^{-3}. Thus obtained values of these parameters, that are not affected by degeneracies, can then be used as input for extracting δ_{CP} from the data collected with a shorter baseline as in the JHF–Kamioka experiment [10].

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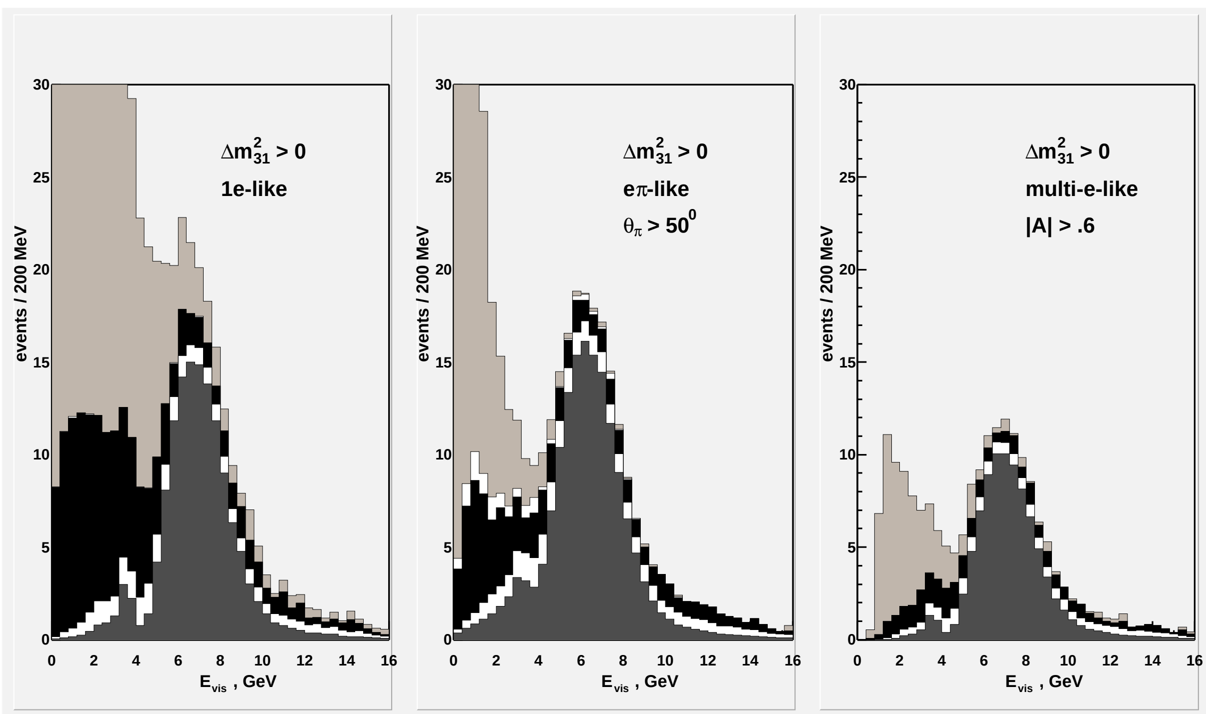

Figure 1: $E_{\rm vis}$ distributions of 1e-like events (left-hand panel), $e\pi$-like events (middle panel), and multi-e-like events (right-hand panel) for $\Delta m^2_{31} > 0$ and incident neutrinos. From bottom, the depicted components are the $\nu_\mu \to \nu_e$ signal (shaded area), intrinsic ν_eCC background (white area), ν_τCC background (black area), ν_μCC background (white area), and the NC background (light-shaded area). Event statistics are for an exposure of 1 Mton×yr.

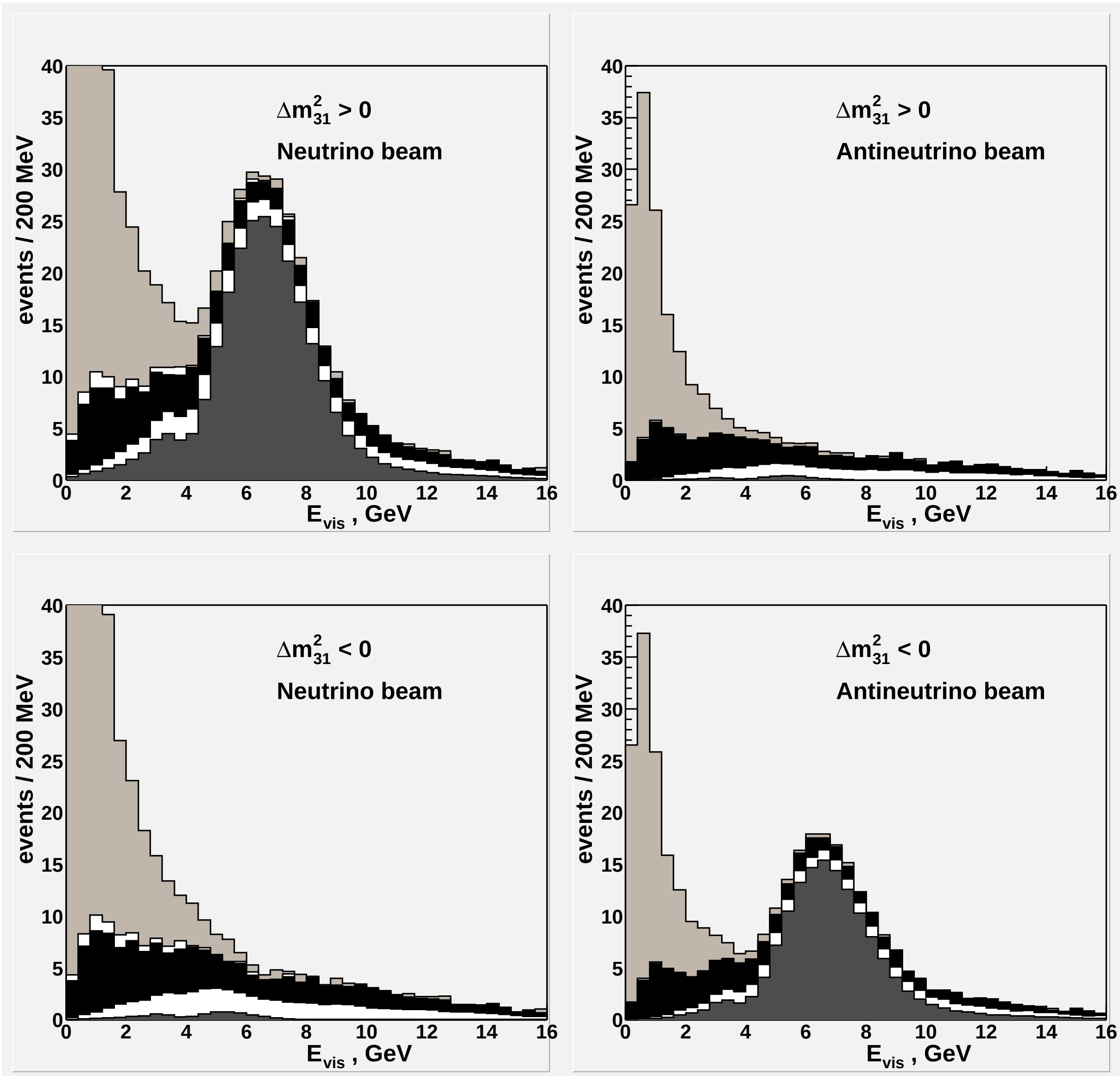

Figure 2: Combined $E_{\rm vis}$ distributions of $e\pi$-like and multi-e-like events for incident neutrinos and antineutrinos (left- and right-hand panels) and for positive and negative values of Δm^2_{31} (top and bottom panels). From bottom, the depicted components are the $\nu_\mu \to \nu_e$ signal (shaded area), intrinsic ν_eCC background (white area), ν_τCC background (black area), ν_μCC background (white area), and the NC background (light-shaded area). Event statistics are for equal ν and $\bar{\nu}$ exposures of 1 Mton$\times$yr.

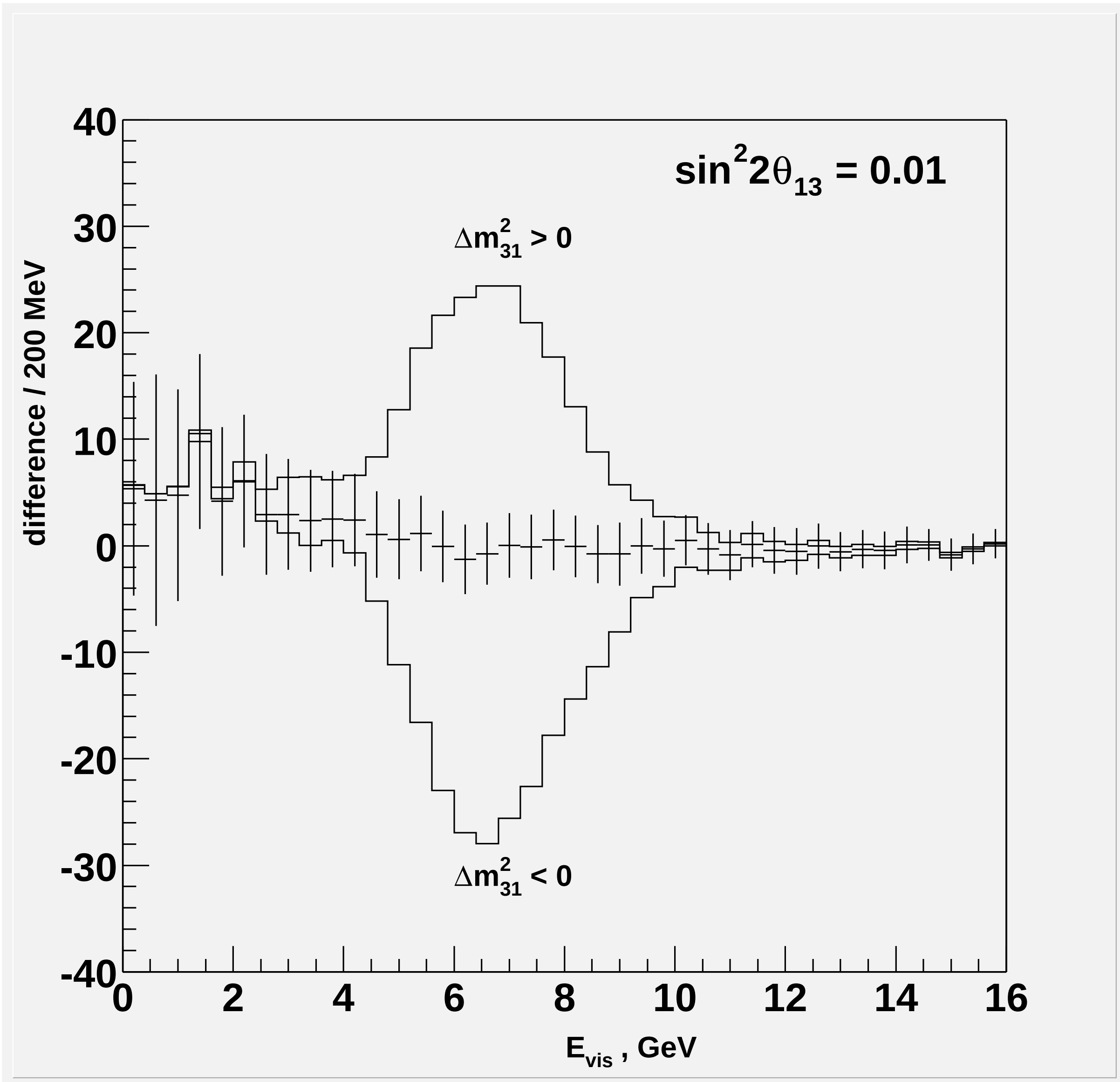

Figure 3: The difference between the $E_{\rm vis}$ distributions for the ν and $\bar{\nu}$ settins of the beam, assuming unequal ν and $\bar{\nu}$ exposures of 1.0 and 1.8 Mton×yr, respectively. The upper and lower histograms are for $\Delta m^2_{31} > 0$ and $\Delta m^2_{31} < 0$, respectively. The expectation for $\sin^2 2\theta_{13} = 0$ is illustrated by points with error bars that depict the statistical uncertainty.